Space Shuttle Launch Era Spacecraft Injection Errors and DSN Initial Acquisition

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The initial acquisition of a spacecraft by the Deep Space Network (DSN) is a critical mission event. This results from the importance of rapidly evaluating the health and trajectory of a spacecraft in the event that immediate corrective action might be required. Further, the DSN initial acquisition is always complicated by the most extreme tracking rates of the mission. DSN initial acquisition characteristics will change considerably in the upcoming Space Shuttle launch era. This article describes the method being developed for evaluating the impact of spacecraft injection errors on DSN initial acquisitions during the Space Shuttle launch era.

I. Introduction

The initial acquisition of a spacecraft by the Deep Space Network (DSN) is a critical mission event. This results from the importance of rapidly evaluating the health and trajectory of a spacecraft in the event that immediate corrective action might be required. Further, the DSN initial acquisition is always complicated by the most extreme tracking rates of the mission. DSN initial acquisition characteristics will change considerably in the upcoming Space Shuttle launch era. Therefore, it is desirable to understand how given injection errors at spacecraft separation from the upper stage launch vehicle (carried into orbit by the Space Shuttle) impact the DSN initial acquisition, and how this information can be factored into injection accuracy requirements to be levied on the Space Transportation System (STS). The approach developed in this article begins with the DSN initial acquisition parameters, generates a covariance matrix, and maps this covariance matrix backward to the spacecraft injection, thereby greatly simplifying the task of levying accuracy requirements on the STS, by providing such requirements in a format both familiar and convenient to STS.

Section II of the article describes the Space Transporation System, while Section III describes the method developed to map DSN initial acquisition accuracy requirements back to a STS formatted spacecraft injection covariance matrix.

II. The Space Transportation System (STS)

The basic elements of the STS are the Space Shuttle, which will carry its payload to a nominal 275-kilometer (150-nautical-mile) circular orbit, and the payload, which for deep space missions will consist of the spacecraft mated to a staging vehicle. The staging vehicles currently under consideration are the Boeing Inertial Upper Stage (IUS) with or without a spinning kick stage (e.g., Star 48), the General Dynamics modified single-stage liquid Centaur, or the Martin hypergolic Transtage. Basic tracking support for STS is handled by the Tracking and Data Relay Satellite System (TDRSS), with Ground Spaceflight Tracking and Data Network (GSTDN) (and in approximately 1985, the Consolidated DSN) as a backup, and launch support and control provided by Johnson Space Center (JSC). It is assumed that formal handover to JPL mission control occurs at the initial acquisition of the spacecraft by a DSN station.

It is of interest to note the differences between initial acquisitions in the expendable launch vehicle era and those in the STS era. In the expendables' era, initial acquisition generally occurred over the same Deep Space Station (DSS) regardless of launch date or time. Trajectory dispersions were relatively small due to the precise control of the launch vehicle cryogenic propellant flow rate, and the shortness of flight time to injection, which minimized guidance system errors. In the Shuttle era, the initial acquisition DSS can change from day to day, and possibly from one Shuttle orbit revolution to the next. Additionally, larger trajectory dispersions are likely because of the possible usage of solid fuel upper stages and longer elapsed times from launch to injection (dependent on the guidance scheme used), with a correspondingly larger effect through guidance system hardware inaccuracies.

A. Spacecraft Injection Errors

Spacecraft injection errors are normally specified in the form of a covariance matrix (Λ_0) representing dispersions of the nominal state (i.e., position, velocity, and time). These dispersions reflect uncertainty in attitude, propellant and dry mass of the stages, thrust and specific impulses, thrust vector control response, control limit cycles (dead bands), on-board software bias errors, timing errors, modeling errors, and initial parking orbit uncertainities. Because of the large number of parameters representing both performance and hardware, and the various guidance strategies involved, such as a ground update of the parking orbit state, or attitude update of the inertial measuring unit (IMU) utilizing star scanners, the injection covariance matrix (Λ_0) is usually generated by Monte Carlo simulation techniques (Ref. 1).

B. Figure of Merit

The figure of merit (FOM) has been adopted as a means of defining the spacecraft propellant requirements for the post-injection trajectory correction maneuvers required to null injection errors. Thus the FOM allows the spacecraft designers to determine the required propellant mass, and serves as a key parameter for evaluating launch errors from all sources. This results in a launch phase optimization of guidance, navigation, and control subsystems. A mapping matrix (U) from injection to a nominal first maneuver time (e.g., 10 days for outer planet missions) is generated. This 3×6 mapping matrix relates injection errors to elements of the maneuver $\Delta \nu$, namely, $\Delta \dot{x}$, $\Delta \dot{y}$, and $\Delta \dot{z}$, at the destination (i.e., target planet). Let:

$$\Lambda_{\Delta \nu} = U \Lambda_0 U^T$$

$$FOM \stackrel{\Delta}{=} (\text{trace } \Lambda_{\Delta \nu})^{1/2}$$

Thus, the FOM is not actually the one sigma maneuver, but is somewhat greater. The statistical significance of the FOM will not be discussed here (Ref. 1); nevertheless, injection accuracy requirements via this process have been simplified to a scalar number and a mapping matrix.

In a fashion similar to the FOM, it is the intent here to simplify the DSN initial acquisition accuracy requirement interface to the STS.

C. DSN Initial Acquisition Requirements on STS

The DSN initial acquisition prediction requirements are based on hardware configurations and capabilities. The primary concern is to ensure a two-way acquisition within ten minutes of the earliest opportunity (i.e., spacecraft rise). This ensures that potent tracking data for navigation, especially in the event of nonstandard spacecraft configurations or trajectories, will be generated during the initial tracking pass. At a minimum, the angular dispersions should be less than the acquisition aid antenna beamwidth for angular searches, and frequency dispersions should be less than both the uplink spacecraft frequency prediction uncertainty (~2000 Hz) and the downlink spacecraft frequency prediction uncertainty (~3000 Hz) for frequency searches. The configuration of the initial acquisition DSS includes a 34-m antenna with a 0.27-deg beamwidth, and Block III receivers with tracking loop bandwidths of 152 Hz or less. The 9-meter antenna, which will provide the angular error signals for the 34-m antenna, has a 1-deg beamwidth with a 10-deg beamwidth acquisition aid antenna and wide bandwidth multifunction receivers. An angular error greater than 5-deg and a radial velocity error greater than 130 m/s (2000 Hz) (assuming that the one-way spacecraft frequency prediction uncertainty is 2000 Hz) could adversely affect the acquisition of the downlink and the uplink. Thus to achieve the initial acquisition within 10 minutes of spacecraft rise, the angular and velocity accuracies are required to be:

3σ angular uncertainty $\leqslant 5$ deg

3σ radial velocity uncertainty $\leqslant 130$ m/s

III. Translation of DSN Initial Acquisition Requirements to a Spacecraft Injection Covariance Matrix

Normally, the covariance matrix Λ_0 is mapped forward to initial DSS rise utilizing the state transition matrix. The error ellipsoid is then rotated locally to station coordinates (e.g., azimuth-elevation (az-el), hour angle-declination (HA-dec), or NASA X-Y), and the 1σ errors are evaluated in comparison to DSN initial acquisition requirements. The angular rates of the nominal trajectory are used to obtain timing errors on the events (e.g., rise and maximum elevation). A more effective method is to utilize the DSN requirements to generate a covariance matrix at DSS initial rise, map this covariance matrix backward to injection, and then rotate the matrix locally (at injection time) to the coordinate system type and units the STS uses. This results in a covariance matrix Λ_c expressing DSN initial acquisition constraints. Expressing DSN constraints in this form simplifies the interface in a way similar to the FOM specification. The STS has only to evaluate the constraint covariance matrix by simple mathematical tools described in the remainder of this section.

Given the injection covariance matrix Λ_0 generated by the STS, and the DSN constraint covariance matrix at injection Λ_c as supplied by the flight projects, the problem is reduced to an eigenvalue solution of the following equation:

$$X_{max}^T (\Lambda_0 - \Lambda_c) X_{max} \leqslant 0$$

where X_{max}^T is the normalized eigenvector associated with the largest eigenvalue of the symmetric matrix $(\Lambda_0 - \Lambda_c)$. Violation of the above equation (positive eigenvalues) implies possible DSN acquisition constraint violations.

For positive eigenvalues $(\lambda_i\ (max))$, the probability that DSN constraints will be violated can be computed as follows:

$$\sigma_{0i}^2 = X_{max}^T \Lambda_0 X_{max}$$

$$\sigma_{ci}^2 = X_{max}^T \Lambda_c X_{max}$$

Assuming a Gaussian distribution, and by utilizing asymptotic theorems (i.e., De Moivre-Laplace), the probability that random variable X_i lies between σ_{ci} and σ_{0i} is:

$$\text{probability}\ (\sigma_{ci} \leqslant X_i \leqslant \sigma_{0i}) = 2\left[\text{erf}(1) - \text{erf}\left(\frac{\sigma_{ci}}{\sigma_{0i}}\right)\right]$$

$$= 0.68268 - 2\ \text{erf}\left(\frac{\sigma_{ci}}{\sigma_{0i}}\right)$$

where

$$\text{erf}(-\alpha) = -\text{erf}(\alpha);\quad \text{erf}(\infty) = 1/2$$

The above process is currently being incorporated in a computer program called SSTATS (for Station Statistics). The program will be able to handle the various error coordinate systems, and the various DSS antenna types (i.e., az-el, HA-dec, and NASA X-Y), in addition to the Tracking and Data Relay Satellite (TDRS) coverage.

In a subsequent TDA Progress Report, numerical examples of this method using the SSTATS Program with characteristic Space Shuttle trajectories, will be provided.

IV. Conclusions

A method of reconciling DSN initial acquisition prediction accuracy requirements with injection accuracy requirements has been developed. This method involves the comparison of the spacecraft injection covariance matrix with a backward generated covariance matrix based upon DSN initial acquisition requirements.

Use of this method will allow a simplified interface to be developed between the DSN, the flight projects, and the STS.

Reference

1. Khatib, A. R., and Deaton, A. W., "Shuttle/IUS Trajectory Design for Planetary Missions," AIAA Paper No. 78-1433, August 7, 1978.